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Chapter 2

CONSTRUCTION ASPECTS AND OPERATION PRINCIPLES

The induction machine is basically an a.c. polyphase machine connected to an a.c. power grid, either in the stator or in the rotor. The a.c. power source is, in general, three phase but it may also be single phase. In both cases the winding arrangement on the part of the machine—the primary—connected to the grid (the stator in general) should produce a traveling field in the machine airgap. This traveling field will induce voltages in conductors on the part of the machine not connected to the grid (the rotor, or the mover in general), - the secondary. If the windings on the secondary (rotor) are closed, a.c. currents occur in the rotor.

The interaction between the primary field and secondary currents produces torque from zero rotor speed onward. The rotor speed at which the rotor currents are zero is called the ideal no-load (or synchronous) speed. The rotor winding may be multiphase (wound rotors) or made of bars shortcircuited by end rings (cage rotors).

All primary and secondary windings are placed in uniform slots stamped into thin silicon steel sheets called laminations.

The induction machine has a rather uniform airgap of 0.2 to 3 mm. The largest values correspond to large power, 1 MW or more. The secondary windings may be short-circuited or connected to an external impedance or to a power source of variable voltage and frequency. In the latter case however the IM works as a synchronous machine as it is doubly fed and both stator and rotor-slip frequencies are imposed.

Though historically double stator and double rotor machines have also been proposed to produce variable speed more conveniently, they did not make it to the markets. Today's power electronics seem to move such solutions even further into oblivion.

In this chapter we discuss construction aspects and operation principles of induction machines. A classification is implicit.

The main parts of any IM are

- The stator slotted magnetic core
- The stator electric winding
- The rotor slotted magnetic core
- The rotor electric winding
- The rotor shaft
- The stator frame with bearings
- The cooling system
- The terminal box

The induction machines may be classified many ways. Here are some of them:

- With rotary or linear motion
- Three phase supply or single-phase supply
- With wound or cage rotor

In very rare cases the internal primary is the mover and the external secondary is at a standstill. In most rotary IMs, the primary is the stator and the secondary is the rotor. Not so for linear induction machines. Practically all IMs have a cylindrical rotor and thus a radial airgap between stator and rotor, though, in principle, axial airgap IMs with disk-shaped rotor may be built to reduce volume and weight in special applications.

First we discuss construction aspects of the above mentioned types of IMs and then essentials of operation principles and modes.

2.1. CONSTRUCTION ASPECTS OF ROTARY IMs

Let us start with the laminated cores.

2.1.1. The magnetic cores

The stator and rotor magnetic cores are made of thin silicon steel laminations with unoriented grain to reduce hysteresis and eddy current losses. The stator and rotor laminations are packed into a single stack (Figure 2.1) or in a multiple stack (Figure 2.2). The latter has radial channels (5-15 mm wide) between elementary stacks (50 to 150 mm long) for radial ventilation.

Single stacks are adequate for axial ventilation.

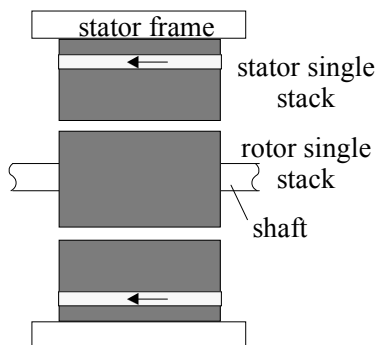


Figure 2.1 Single stack magnetic core

Single-stack IMs have been traditionally used below 100 kW but recently have been introduced up to 2 MW as axial ventilation has been improved drastically. The multistack concept is necessary for large power (torque) with long stacks.

The multiple stacks lead to additional winding losses, up to 10%, in the stator and in the rotor as the coils (bars) lead through the radial channels without

producing torque. Also, the electromagnetic field energy produced by the coils (bar) currents in the channels translate into additional leakage inductances which tend to reduce the breakdown torque and the power factor. They also reduce the starting current and torque. Typical multistack IMs are shown in [Figure 2.2](#).

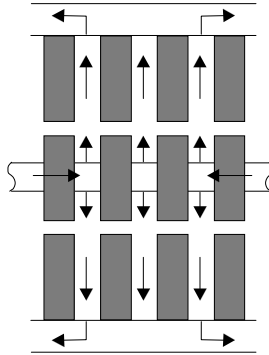


Figure 2.2 Multiple stack IM

For IMs of fundamental frequency up to 300 Hz, 0.5 mm thick silicon steel laminations lead to reasonable core losses 2 to 4 W/Kg at 1T and 50 Hz.

For higher fundamental frequency, thinner laminations are required. Alternatively, anisotropic magnetic powder materials may be used to cut down the core losses at high fundamental frequencies, above 500 Hz, however at lower power factor (see Chapter 3 on magnetic materials).

2.1.2. Slot geometry

The airgap, or the air space between stator and rotor, has to be traveled by the magnetic field produced by the stator. This in turn will induce voltages and produce currents in the rotor windings. Magnetizing air requires large magnetomotive forces (mmfs) or amperturns. The smaller the air (nonmagnetic) gap, the smaller the magnetization mmf. The lower limit of airgap g is determined by mechanical constraints and by the ratio of the stator and slot openings b_{os} , b_{or} to airgap g in order to keep additional losses of surface core and tooth flux pulsation within limits. The tooth is the lamination radial sector between two neighbouring slots.

Putting the windings (coils) in slots has the main merit of reducing the magnetization current. Second, the winding manufacture and placement in slots becomes easier. Third, the winding in slots are better off in terms of mechanical rigidity and heat transmission (to the cores). Finally the total mmf per unit length of periphery (the coil height) could be increased and thus large power IMs could be built efficiently. What is lost is the possibility to build windings (coils) that can produce purely sinusoidal distributed amperturns (mmfs) along

the periphery of the machine airgap. But this is a small price to pay for the incumbent benefits.

The slot geometry depends mainly on IM power (torque) level and thus on the type of magnetic wire—with round or rectangular cross section—from which the coils of windings are made. With round wire (random wound) coils for small power IMs (below 100 kW in general), the coils may be introduced in slots wire by wire and thus the slot openings may be small (Figure 2.3a). For preformed coils (in large IMs), made, in general, of rectangular cross-section wire, open or semiopen slots are used (Figure 2.3b, c).

In general, the slots may be rectangular, straight trapezoidal, or rounded trapezoidal. Open and semiopen slots tend to be rectangular (Figure 2.3b, c) in shape and the semiclosed are trapezoidal or rounded trapezoidal (Figure 2.3a).

In an IM, only slots on one side are open, while on the other side, they are semiclosed or semiopen.

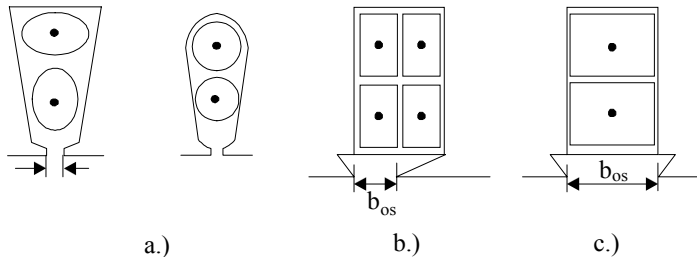


Figure 2.3 Slot geometries to locate coil windings
a.) semiclosed b.) semiopen c.) open

The reason is that a large slot opening, b_{os} , per gap, g , ratio ($b_{os}/g > 6$) leads to lower average flux density, for given stator mmf and to large flux pulsation in the rotor tooth, which will produce large additional core losses. In the airgap flux density harmonics lead to parasitic torques, noise, and vibration as presented in subsequent, dedicated, chapters. For semiopen and semiclosed slots, $b_{os}/g \cong (4-6)$ in general. For the same reasons, the rotor slot opening per airgap $b_{or}/g \cong 3-4$ wherever possible. Too small a slot opening per gap ratio leads to a higher magnetic field in the slot neck (Figure 2.3) and thus to a higher slot leakage inductance, which causes lower starting torque and current and lower breakdown torque.

Slots as in Figure 2.3 are used both for stator and wound rotors. Rotor slot geometry for cage-rotors is much more diversified depending upon

- Starting and rated load constraints (specifications)
- Constant voltage/frequency (V/f) or variable voltage/frequency supply operation
- Torque range.

Less than rated starting torque, high efficiency IMs for low power at constant V/f or for variable V/f may use round semiclosed slots (Figure 2.4a).

Rounded trapezoidal slots with rectangular teeth are typical for medium starting torque (around rated value) in small power IMs (Figure 2.4b).

Closed rotor slots may be used to reduce noise and torque pulsations for low power circulating fluid pumps for homes at the expense of large rotor leakage inductance; that is, lower breakdown torque. In essence the iron bridge (0.5 to 1 mm thick), above the closed rotor slot, already saturates at 10 to 15% of rated current at a relative permeability of 50 or less that drops further to 15 to 20 for starting conditions (zero speed, full voltage).

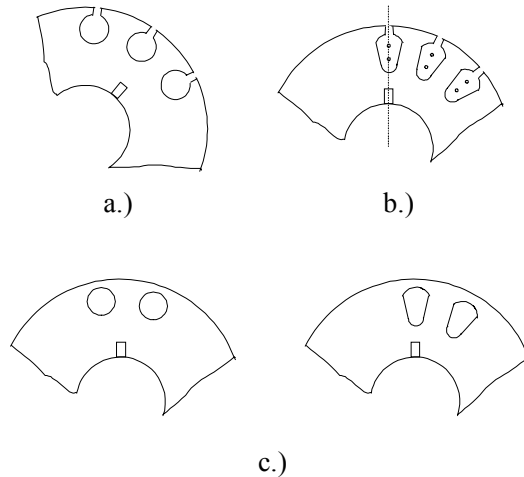


Figure 2.4 Rotor slots for cage rotors

a.) semiclosed and round b.) semiclosed and round trapezoidal c.) closed slots

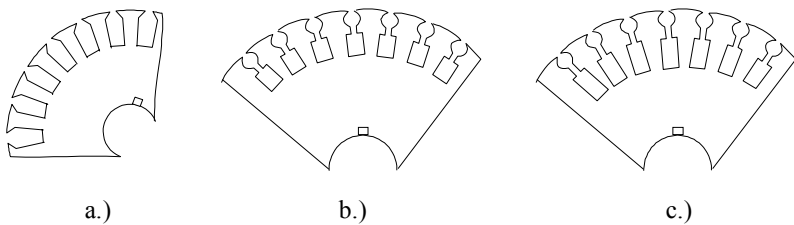


Figure 2.5 Rotor slots for low starting current IMs

a.) high slip, high starting torque b.) moderate starting torque c.) very high starting torque

For high starting torque, high rated slip (lower rated speed with respect to ideal no-load speed), rectangular deep bar rotor slots are used (Figure 2.5a). Inverse trapezoidal or double cage slots are used for low starting current and moderate and large starting torque (Figure 2.5b, c). In all these cases, the rotor slot leakage inductance increases and thus the breakdown torque is reduced to as low as 150 to 200% rated torque.

More general, optimal shape cage rotor slots may be generated through direct FEM optimization techniques to meet desired performance constraints for special applications. In general, low stator current and moderate and high starting torque rely on the rotor slip frequency effect on rotor resistance and leakage inductance.

At the start, the frequency of rotor currents is equal to stator (power grid) frequency f_1 , while at full load $f_{sr} = S_n f_1$; S_n , the rated slip, is about 0.08 and less than 0.01 in large IMs:

$$S = \frac{f_1 - np_1}{f_1}; \quad n - \text{speed in rps} \quad (2.1)$$

p_1 is the number of spatial periods of airgap traveling field wave per revolution produced by the stator windings:

$$B_{g0}(x, t) = B_{g_{m0}} \cos(p_1 \theta_1 - \omega_1 t) \quad (2.2)$$

θ_1 -mechanical position angle; $\omega_1 = 2\pi f_1$.

Remember that, for variable voltage and frequency supply (variable speed), the starting torque and current constraints are eliminated as the rotor slip frequency Sf_1 is always kept below that corresponding to breakdown torque.

Very important in variable speed drives is efficiency, power factor, breakdown torque, and motor initial or total costs (with capitalized loss costs included).

2.1.3. IM windings

The IM is provided with windings both on the stator and on the rotor. Stator and rotor windings are treated in detail in Chapter 4.

Here we refer only to a primitive stator winding with 6 slots for two poles (Figure 2.6).

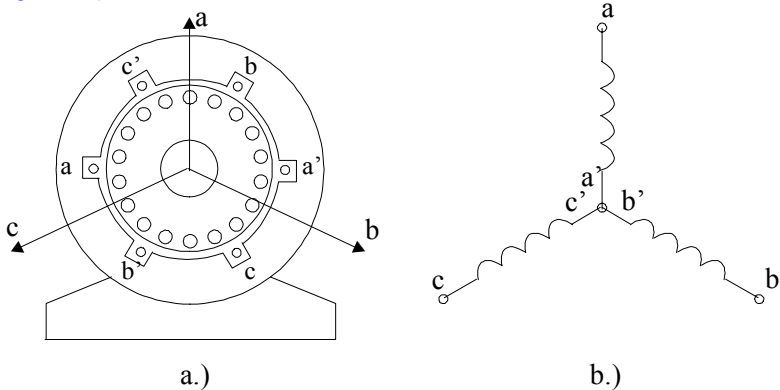


Figure 2.6 Primitive IM with 6 stator slots and cage rotor

Each phase is made of a single coil whose pitch spans half of rotor periphery. The three phases (coils) are space shifted by 120° . For our case there are 120° mechanical degrees between phase axes as $p_1 = 1$ pole pair. For $p_1 = 2, 3, 4, 5, 6$, there will be $120^\circ/p_1$ mechanical degrees between phase axes.

The airgap field produced by each phase has its maximum in the middle of the phase coil (Figure 2.6) and, with the slot opening eliminated, it has a rectangular spatial distribution whose amplitude varies sinusoidally in time with frequency f_1 (Figure 2.7).

It is evident from Figure 2.7 that when the time angle θ_t electrically varies by $\pi/6$, so does the fundamental maximum of airgap flux density with space harmonics neglected, a travelling wavefield in the airgap is produced. Its direction of motion is from phase a to phase b axis, if the current in phase a leads (in time) the current in phase b, and phase b leads phase c. The angular speed of this field is simply ω_1 , in electrical terms, or ω_1/p_1 in mechanical terms (see also Equation (2.2)).

$$\Omega_1 = 2\pi n_1 = \omega_1 / p_1 \quad (2.3)$$

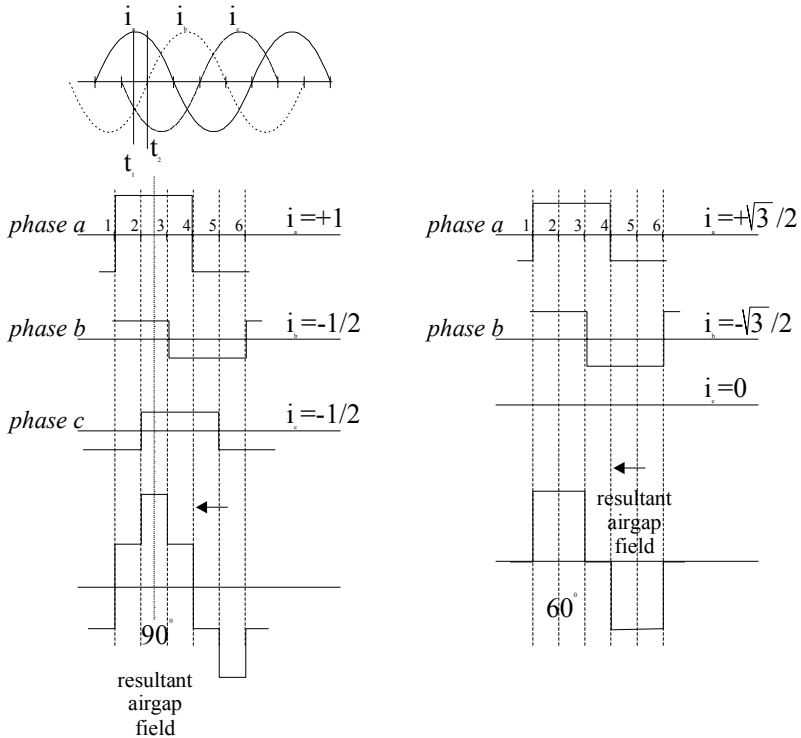


Figure 2.7 Stator currents and airgap field at times t_1 and t_2 .

So n_1 , the traveling field speed in rps, is

$$n_1 = f_1 / p_1 \quad (2.4)$$

This is how the ideal no load speed for 50(60) Hz is 3000/3600 rpm for $p_1 = 1$, 1500/1800 rpm for $p_1 = 2$ and so on.

As the rated slip S_n is small (less than 10% for most IMs), the rated speed is only slightly lower than a submultiple of f_1 in rps. The crude configuration in [Figure 2.7](#) may be improved by increasing the number of slots, and by using two layers of coils in each slot. This way the harmonics content of airgap flux density diminishes, approaching a better pure traveling field, despite the inherently discontinuous placement of conductors in slots.

A wound stator is shown in [Figure 2.8](#). The three phases may be star or delta connected. Sometimes, during starting, the connection is changed from star to delta (for delta-designed IMs) to reduce starting currents in weak local power grids.

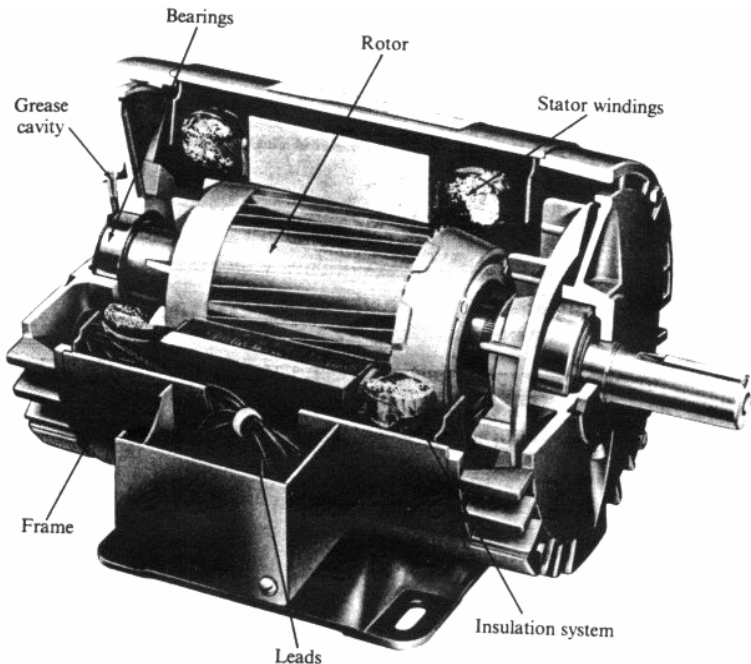


Figure 2.8 IM wound three-phase stator winding with cage rotor

Wound rotors are built in a similar way ([Figure 2.9](#)). The slip rings are visible to the right. The stator-placed brush system is not. Single-phase-supply IMs have, on the other hand, in general, two windings on the stator.

The main winding (m) and the auxiliary (or starting) one (a) are used to produce a traveling field in the airgap. Similar to the case of three phases, the

two windings are spatially phase shifted by 90° (electrical) in general. To phase shift the current in the auxiliary winding, a capacitor is used.

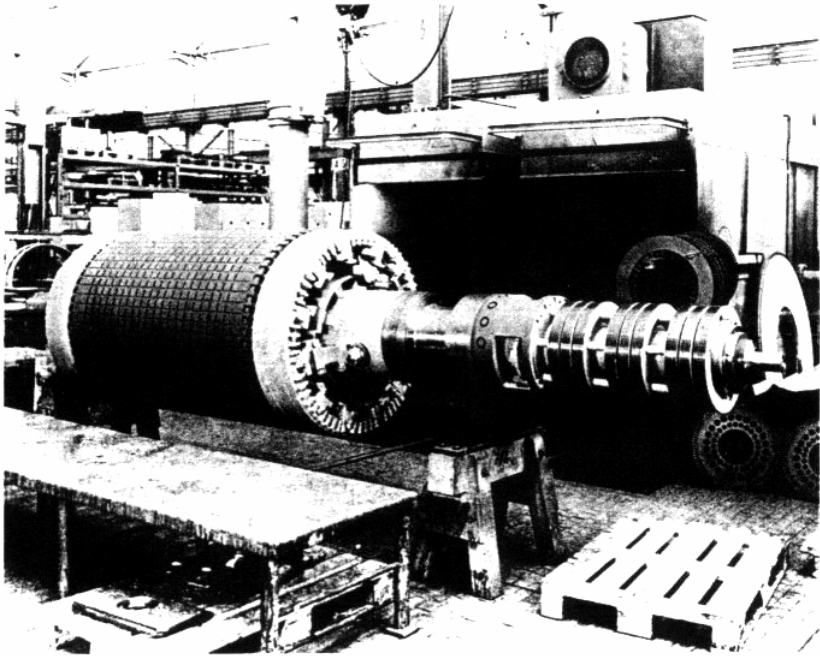


Figure 2.9 Three-phase wound rotor

In reversible motion applications, the two windings are identical. The capacitor is switched from one phase to the other to change the direction of traveling field.

When auxiliary winding works continuously, each of the two windings uses half the number of slots. Only the number of turns and the wire cross-section differ.

The presence of auxiliary winding with capacitance increases the torque, efficiency, and power factor. In capacitor-start low-power (below 250 W) IMs, the main winding occupies $2/3$ of the stator slots and the auxiliary (starting) winding only $1/3$. The capacitor winding is turned off in such motors by a centrifugal or time relay at a certain speed (time) during starting. In all cases, a cage winding is used in the rotor (Figure 2.10). For very low power levels (below 100 W in general), the capacitor may be replaced by a resistance to cut cost at the expense of a lower efficiency and power factor.

Finally, it is possible to produce a traveling field with a single phase concentrated coil winding with shaded poles (Figure 2.11). The short-circuiting ring is retarding the magnetic flux of the stator in the shaded pole area with respect to the unshaded pole area.

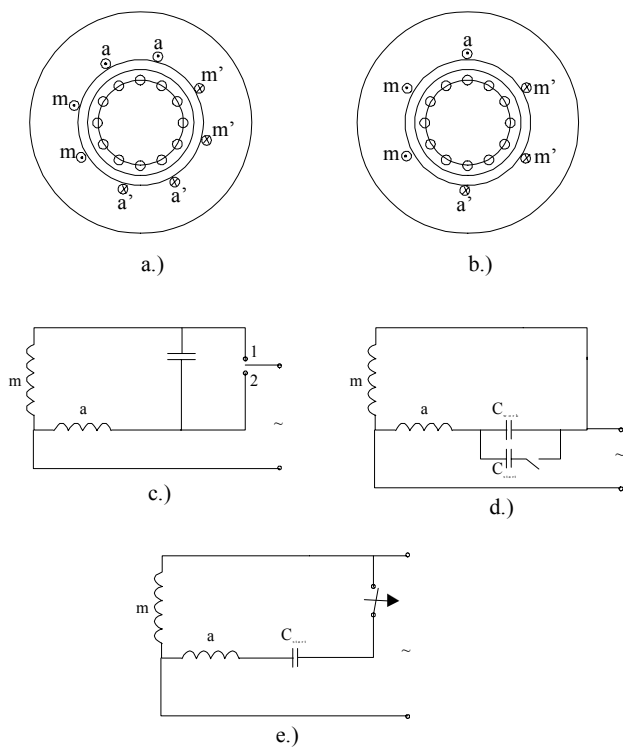


Figure 2.10 Single phase supply capacitor IMs
a.) primitive configuration with equally strong windings
b.) primitive configuration with 2/3, 1/3 occupancy windings
c.) reversible motor d.) dual capacitor connection
e.) capacitor start-only connection

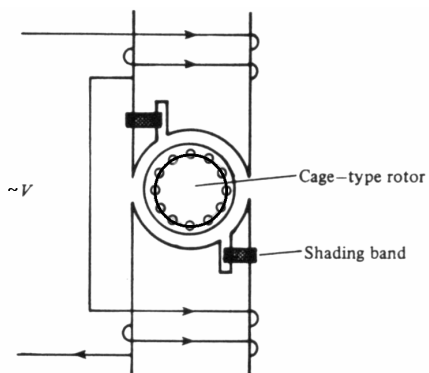


Figure 2.11 Single phase (shaded pole) IM

The airgap field has a traveling component and the motor starts rotating from the unshaded to the shaded pole zone. The rotor has a cage winding. The low cost and superior ruggedness of shaded pole single phase IM is paid for by a lower efficiency and power factor. This motor is more of historical importance and is seldom used, usually below 100 W, where cost is the prime concern.

2.1.4. Cage rotor windings

As mentioned above, the rotor of IMs is provided with single or double cage windings (Figure 2.12), in addition to typical three phase windings on wound rotors.

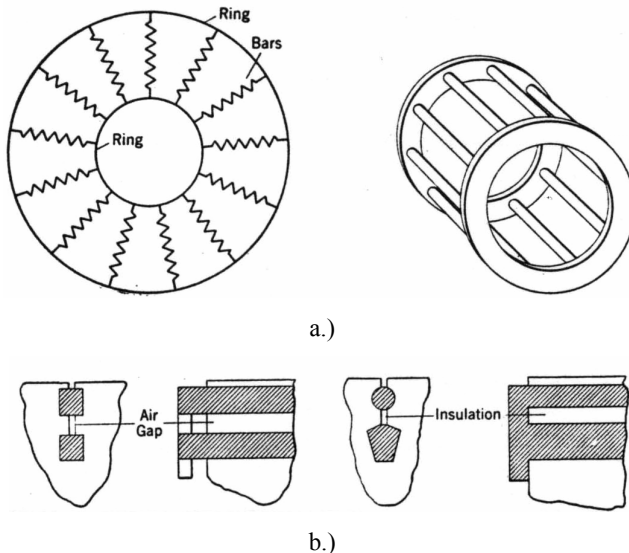


Figure 2.12 Cage rotor windings
a.) single cage b.) double cage

The cage bars and end rings are made of diecast aluminum for low and medium power and from brass or copper for high powers. For medium and high powers, the bars are silver-rings-welded to end to provide low resistance contact.

For double cages brass may be used (higher resistivity) for the upper cage and copper for the lower cage. In this case, each cage has its own end ring, mainly due to thermal expansion constraints.

For high efficiency IMs copper tends to be preferred due to higher conductivity, larger allowable current density, and working temperatures.

The diecasting of aluminum at rather low temperatures results in low rotor mass production costs for low power IMs.

Energy efficient, totally enclosed squirrel cage three phase motor
Type M2BA 280 SMB, 90 kW, IP 55, IC 411, 1484 r/min, weight 630 kg

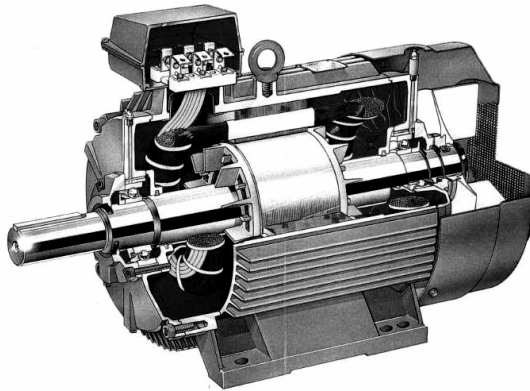


Figure 2.13 Cutaway view of a modern induction motor

The debate over aluminum or copper is not yet decided and both materials are likely to be used depending on the application and power (torque) level.

Although some construction parts such as frames, cooling system, shafts, bearings, and terminal boxes have not been described here, we will not dwell on them at this time as they will be discussed again in subsequent chapters. Instead, [Figure 2.13](#) presents a rather complete cutaway view of a fairly modern induction motor. It has a single stack magnetic core, thus axial ventilation is used by a fan on the shaft located beyond the bearings. The heat evacuation area is increased by the finned stator frame. This technology has proven practical up to 2 MW in low voltage IMs.

The IM in [Figure 2.13](#) has a single-cage rotor winding. The stator winding is built in two layers out of round magnetic wire. The coils are random wound. The stator and rotor slots are of the semiclosed type. Configuration in [Figure 2.13](#) is dubbed as totally enclosed fan cooled (TEFC), as the ventilator is placed outside bearings on the shaft.

It is a low voltage IM (below 690 V RMS–line voltage).

2.2. CONSTRUCTION ASPECTS OF LINEAR INDUCTION MOTORS

In principle, for each rotary IM there is a linear motion counter-part. The imaginary process of cutting and unrolling the rotary machine to obtain the linear induction motor (LIM) is by now classic ([Figure 2.14](#)). [1]

The primary may now be shorter or larger than the secondary. The shorter component will be the mover. In [Figure 2.14](#) the primary is the mover. The primary may be double sided ([Figure 2.14d](#)) or single sided ([Figure 2.14 c, e](#)).

The secondary material is copper or aluminum for the double-sided LIM and it may be aluminum (copper) on solid iron for the single-sided LIM. Alternatively, a ladder conductor secondary placed in the slots of a laminated core may be used, as for cage rotor rotary IMs (Figure 2.14c). This latter case is typical for short travel (up to a few meters) low speed (below 3 m/s) applications.

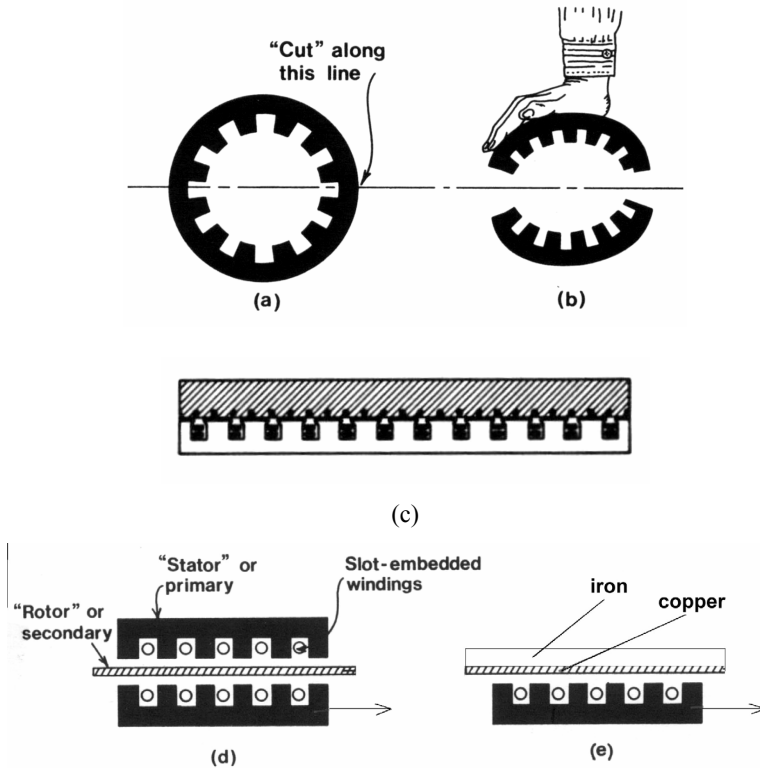


Figure 2.14 Cutting and unrolling process to obtain a LIM

Finally, the secondary solid material may be replaced by a conducting fluid (liquid metal), when a double sided linear induction pump is obtained. [2]

All configurations on Figure 2.14 may be dubbed as flat ones. The primary winding produces an airgap field with a strong traveling component at the linear speed u_s .

$$u_s = \tau \cdot \frac{\omega_l}{\pi} = 2\tau f_l \quad (2.5)$$

The number of pole pairs does not influence the ideal no-load linear speed u_s . Incidentally, the peripheral ideal no-load speed in rotary IMs has the same

formula (2.5) where τ is the pole pitch (the spatial semiperiod of the traveling field).

In contrast to rotary IMs, the LIM has an open magnetic structure along the direction of motion. Additional phenomena called longitudinal effects occur due to this. They tend to increase with speed, deteriorating the thrust, efficiency, and power factor performance. Also, above 3 to 5 m/s speed, the airgap has to be large (due to mechanical clearance constraints): in general, 3 to 12 mm. This leads to high magnetization currents and thus a lower power factor than in rotary IMs.

However, the LIM produces electromagnetic thrust directly and thus eliminates any mechanical transmission in linear motion applications (transportation).

Apart from flat LIM, tubular LIMs may be obtained by rerolling the flat LIM around the direction of motion ([Figure 2.15](#)).

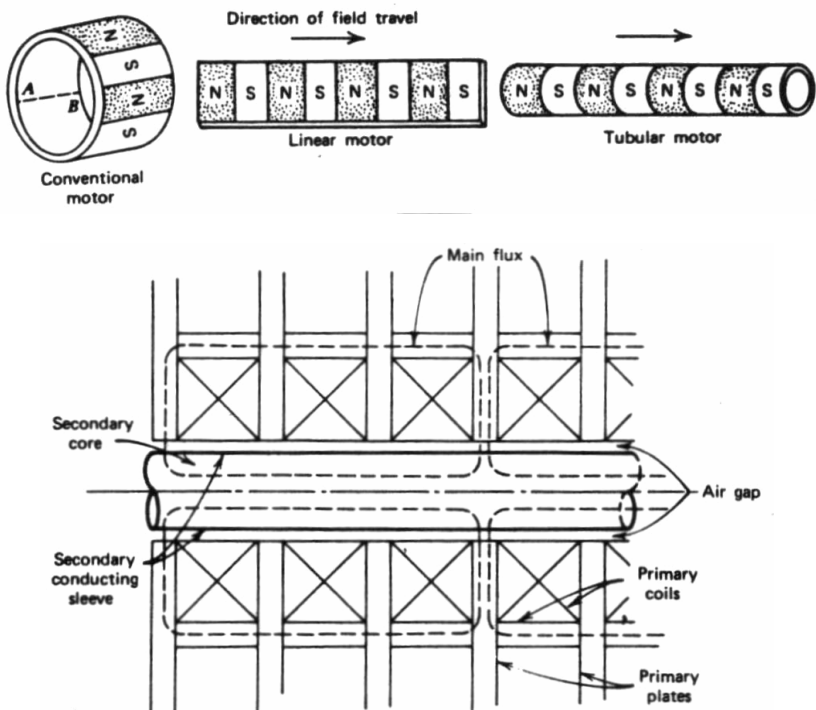


Figure 2.15 The tubular linear induction motor

The coils of primary winding are now of circular shape. The rotor may be an aluminum cylinder on solid iron. Alternatively, a secondary cage may be built. In this case the cage is made of ring shape-bars. Transverse laminations of disc shape may be used to make the magnetic circuit easy to manufacture, but

care must be excersized to reduce the core losses in the primary. The blessing of circularity renders this LIM more compact and proper for short travels (1 m or less).

In general, LIMs are characterized by a continuous thrust density (N/cm^2 of primary) of up to 2 (2.5) N/cm^2 without forced cooling. The large values correspond to larger LIMs. The current LIM use for a few urban transportation systems in North America, Middle East, and East Asia has proved that they are rugged and almost maintenance free. More on LIMs in Chapter 20.

2.3. OPERATION PRINCIPLES OF IMs

The operation principles are basically related to torque (for rotary IMs) and, respectively, thrust (for LIMs) production. In other words, it is about forces in traveling electromagnetic fields. Or even simpler, why the IM spins and the LIM moves linearly. Basically the torque (force) production in IMs and LIMs may be approached via

- Forces on conductors in a travelling field
- The Maxwell stress tensor [3]
- The energy (coenergy) derivative
- Variational principles (Lagrange equations) [4]

The electromagnetic traveling field produced by the stator currents exists in the airgap and crosses the rotor teeth to embrace the rotor winding (rotor cage)—Figure 2.16. Only a small fraction of it radially traverses the top of the rotor slot which contains conductor material.

It is thus evident that, with rotor and stator conductors in slots, there are no main forces experienced by the conductors themselves. Therefore, the method of forces experienced by conductors in fields does not apply directly to rotary IMs with conductors in slots.

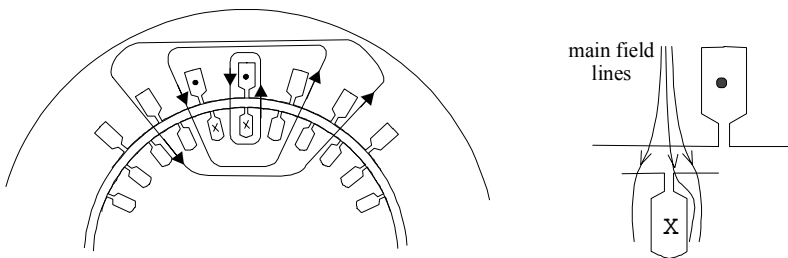


Figure 2.16 Flux paths in IMs

The current occurs in the rotor cage (in slots) because the magnetic traveling flux produced by the stator in any rotor cage loop varies in time even at zero speed (Figure 2.17). If the cage rotor rotates at speed n (in rps), the stator-produced traveling flux density in the airgap (2.2) moves with respect to the rotor with the relative speed n_{sr} .

$$n_{sr} = \frac{f_1}{p_1} - n = S \cdot \frac{f_1}{p_1} \quad (2.6)$$

In rotor coordinates, (2.2) may be written as.

$$B(\theta_r, t) = B_m \cos(p_1 \theta_2 - S \omega_1 t) \quad (2.7)$$

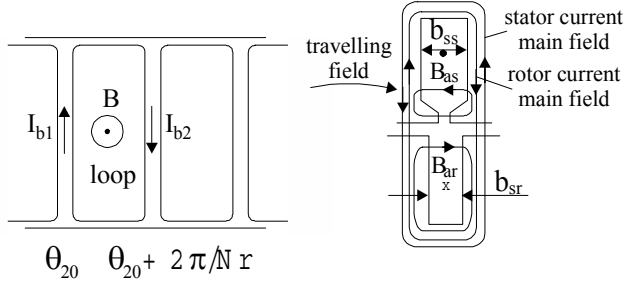


Figure 2.17 Traveling flux crossing the rotor cage loops (a), leakage and main fields (b)

Consequently, with the cage bars in slots, according to electromagnetic induction law, a voltage is induced in loop 1 of the rotor cage and thus a current occurs in it such that its reaction flux opposes the initial flux.

The current which occurs in the rotor cage, at rotor slip frequency \$Sf_1\$ (see (2.7)), produces a reaction field which crosses the airgap. This is the main reaction field. Thus the resultant airgap field is the product of both stator and rotor currents. As the two currents tend to be more than \$2\pi/3\$ when shifted, the resultant (magnetization) current is reasonably low; in fact, it is 25 to 60% of the rated current depending on the machine airgap \$g\$ to pole pitch \$\tau\$ ratio. The higher the ratio \$\tau/g\$, the smaller the magnetization current in p.u.

The stator and rotor currents also produce leakage flux paths crossing the slots: \$B_{as}\$ and \$B_{ar}\$.

According to the Maxwell stress tensor theory, at the surface border between mediums with different magnetic fields and permeabilities (\$\mu_0\$ in air, \$\mu \neq \mu_0\$ in the core), the magnetic field produces forces. The interaction force component perpendicular to the rotor slot wall is. [3]

$$F_{tn} = \frac{B_{ar}(\theta_r, t)B_{tr}(\theta_r, t) - \mu_0}{\mu_0} n_{tooth} \quad (2.8)$$

The magnetic field has a radial (\$B_{tr}\$) and a tangential (\$B_{ar}\$) component only.

Now, for the rotor slot, \$B_{ar}(\theta_r)\$-tangential flux density-is the slot leakage flux density.

$$B_{ar}(\theta_r) = \frac{\mu_0 I_b(\theta_r, t)}{b_{sr}} \quad (2.9)$$

The radial flux density that counts in the torque production is that produced by the stator currents, $B_{tr}(\theta_r)$, in the rotor tooth.

$$B_{tr}(\theta_r, t) = B(\theta_r, t) \cdot \frac{b_{tr} + b_{sr}}{b_{sr}} \quad (2.10)$$

In (2.10), b_{tr} is the mean rotor tooth width while $B(\theta_r, t)$ is the airgap flux density produced by the stator currents in the airgap.

When we add the specific Maxwell stress tensors [1] on the left and on the right side walls of the rotor slot we should note that the normal direction changes sign on the two surfaces. Thus the addition becomes a subtraction.

$$f_{tooth} \left(\text{N/m}^2 \right) = - \left(\frac{B_{ar}(\theta_r + \Delta\theta, t) B_{tr}(\theta_r + \Delta\theta, t)}{\mu_0} - \frac{B_{ar}(\theta_r, t) B_{tr}(\theta_r, t)}{\mu_0} \right) \quad (2.11)$$

Essentially the slot leakage field B_{ar} does not change with $\Delta\theta$ —the radial angle that corresponds to a slot width.

$$f_{tooth} \left(\text{N/m}^2 \right) = - \frac{B_{ar}(\theta_r, t)}{\mu_0} (B_{tr}(\theta_r + \Delta\theta, t) - B_{tr}(\theta_r, t)) \quad (2.12)$$

The approximate difference may be replaced by a differential when the number of slots is large. Also from (2.9):

$$f_{tooth} \left(\text{N/m}^2 \right) = - \frac{I_b(\theta_r, t)}{b_{sr}} \cdot \frac{\Delta B(\theta_r, t)}{\Delta\theta_{slot}} \cdot \frac{(b_{tr} + b_{sr})}{b_{sr}} \cdot \Delta\theta_{slot} \quad (2.13)$$

Therefore it is the change of stator produced field with θ_r , the traveling field existence, that produces the tangential force experienced by the walls of each slot. The total force for one slot may be obtained by multiplying the specific force in (2.13) by the rotor slot height and by the stack length.

It may be demonstrated that with a pure traveling field and rotor current traveling wave $I_b(\theta_r, t)$, the tangential forces on each slot pair of walls add up to produce a smooth torque. Not so if the field is not purely traveling.

Based on same rationale, an opposite direction tangential force on stator slot walls may be calculated. It is produced by the interaction of stator leakage field with rotor main reaction field. This is to be expected as action equals reaction according to Newton's third law. So the tangential forces that produce the torque occur on the tooth radial walls. Despite this reality, the principle of IM is traditionally explained by forces on currents in a magnetic field.

It may be demonstrated that, mathematically, it is correct to “move” the rotor currents from rotor slots, eliminate the slots and place them in an infinitely thin conductor sheet on the rotor surface to replace the actual slot-cage rotor configuration (Figure 2.18). This way the tangential force will be exerted directly on the “rotor” conductors. Let us use this concept to explain further the operation modes of IM.

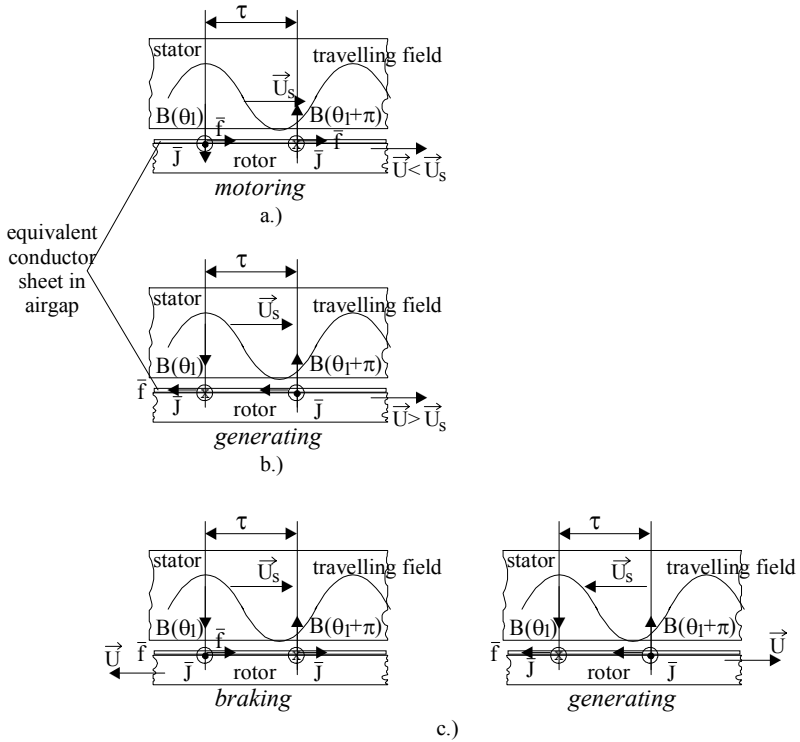


Figure 2.18 Operation modes of IMs

a.) motoring: $\vec{U} < \vec{U}_s$ both in the same direction

b.) generating: $\vec{U} > \vec{U}_s$; both in the same direction

c.) braking: $\vec{U}$ opposite to $\vec{U}_s$; either $\vec{U}$ or $\vec{U}_s$ changes direction.

The relative speed between rotor conductors and stator traveling field is $\vec{U} - \vec{U}_s$, so the induced electrical field in the rotor conductors is.

$$\vec{E} = (\vec{U} - \vec{U}_s) \times \vec{B} \quad (2.14)$$

As the rotor cage is short-circuited, no external electric field is applied to it, so the current density in the rotor conductor $\vec{J}$ is

$$\vec{J} = \sigma_{Al} \vec{E} \quad (2.15)$$

Finally, the force (per unit volume) exerted on the rotor conductor by the traveling field, $\vec{f}_t$, is

$$\vec{f}_t = \vec{J} \times \vec{B} \quad (2.16)$$

Applying these fundamental equations for rotor speed $\vec{U}$ and field speed $\vec{U}_s$ in the same direction we obtain the motoring mode for $\vec{U} < \vec{U}_s$, and, respectively, the generating mode for $\vec{U} > \vec{U}_s$, as shown on [Figure 2.17a, b](#). In the motoring mode, the force on rotor conductors acts along the direction of motion while, in the generating mode, it acts against it. In the same time, the electromagnetic (airgap) power P_e is negative.

$$P_e = \vec{f}_t \cdot \vec{U}_s > 0 ; \text{ for motoring } (f_t > 0, U > 0)$$

$$P_e = \vec{f}_t \cdot \vec{U}_s < 0 ; \text{ for generating } (f_t < 0, U > 0) \quad (2.17)$$

This simply means that in the generating mode the active power travels from rotor to stator to be sent back to the grid after losses are covered. In the braking mode ($U < 0$ and $U_s > 0$ or $U > 0$ and $U_s < 0$), as seen in [Figure 2.18c](#), the torque acts against motion again but the electromagnetic power P_e remains positive ($\vec{U}_s > 0$ and $\vec{f}_t > 0$ or $\vec{U}_s < 0$ and $\vec{f}_t < 0$). Consequently, active power is drawn from the power source. It is also drawn from the shaft. The summation of the two is converted into induction machine losses.

The braking mode is thus energy intensive and should be used only at low frequencies and speeds (low U_s and U), in variable speed drives, to “lock” the variable speed drive at standstill under load.

The linear induction motor operation principles and operation modes are quite similar to those presented for rotary induction machines.

2.4. SUMMARY

- The IM is an a.c. machine. It may be energized directly from a three phase a.c. or single phase a.c. power grid. Alternatively it may be energized through a PWM converter at variable voltage (V) and frequency (f).
- The IM is essentially a traveling field machine. It has an ideal no-load speed $n_1 = f_1/p_1$; p_1 is the number of traveling field periods per one revolution.
- The IM main parts are the stator and rotor slotted magnetic cores and windings. The magnetic cores are, in general, made of thin silicon steel sheets (laminations) to reduce the core losses to values such as 2 to 4 W/Kg at 60 Hz and 1 T.
- Three or two phase windings are placed in the primary (stator) slots. Windings are coil systems connected to produce a travelling mmf (amperturns) in the airgap between the stator and the rotor cores.
- The slot geometry depends on power (torque) level and performance constraints.

Starting torque and current, breakdown torque, rated efficiency, and power factor are typical constraints (specifications) for power grid directly energized IMs.

- Two phase windings are used for capacitor IMs energised from a single phase a.c. supply to produce traveling field. Single phase a.c. supply is typical for home appliances.
- Cage windings made of solid bars in slots with end rings are used on most IM rotors. The rotor bar cross-section is tightly related to all starting and running performances. Deep-bar or double-cage windings are used for high starting torque, low starting current IMs fed from the power grid (constant V and f).
- Linear induction motors are obtained from rotary IMs by the cut-and-unroll process. Flat and tubular configurations are feasible with single sided or double sided primary. Either primary or secondary may be the mover in LIMs. Ladder or aluminum sheet or iron are typical for single sided LIM secondaries. Continuous thrust densities up to 2 to 2.5 N/cm² are feasible with air cooling LIMs.
- In general, the airgap g per pole pitch τ ratio is larger than for rotary IM and thus the power factor and efficiency are lower. However, the absence of mechanical transmission in linear motion applications leads to virtually maintenance-free propulsion systems. Urban transportation systems with LIM propulsion are now in use in a few cities from three continents.
- The principle of operation of IMs is related to torque production. By using the Maxwell stress tensor concept it has been shown that, with windings in slots, the torque (due to tangential forces) is exerted mainly on slot walls and not on the conductors themselves.

Stress analysis during severe transients should illustrate this reality. It may be demonstrated that the rotor winding in slots can be “mathematically” moved in the airgap and transformed into an equivalent infinitely thin current sheet. The same torque is now exerted directly on the rotor conductors in the airgap. The LIM with conductor sheet on iron naturally resembles this situation.

- Based on the $\vec{J} \times \vec{B}$ force principle, three operation modes of IM are easily identified.
 - Motoring: $|U| < |U_s|$; U and U_s either positive or negative
 - Generating: $|U| > |U_s|$; U and U_s either positive or negative
 - Braking: ($U > 0$ & $U_s < 0$) or ($U < 0$ & $U_s > 0$)
- For the motoring mode, the torque acts along the direction motion while, for the generator mode, it acts against it as it does during braking mode. However, during generating the IM returns some power to the grid, after covering the losses, while for braking it draws active power also from the power grid.
- Generating is energy-conversion advantageous while braking is energy intensive. Braking is recommended only at low frequency and speed, with variable V/f PWM converter supply, to stall the IM drive on load (like in overhead cranes). The energy consumption is moderate in such cases (as the frequency is small).

2.5. REFERENCES

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